University of Nevada, Reno

Methodology for Roughness-Speed Relationship with SHRP2 Naturalistic Driving Study Data

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by

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ABSTRACT

Road and traffic factors that influence speed have attracted interest for modeling vehicle fuel consumption and traffic safety. While the influence of geometric design and traffic operation factors have been well studied, the relationship between pavement surface roughness and vehicle speed was not well established in previous studies, mainly because of data limitations. The authors applied a new dataset, Naturalistic Driving Study (NDS) data of the Strategic Highway Research Program 2 (SHRP 2), for studying the roughness-speed relationship. A method was developed to identify the roughness-speed relationship under different road and traffic conditions. The International Roughness Index (IRI) was employed to describe the pavement roughness condition in this research. The new method can be applied to reveal a roughness-speed relationship of different road and traffic conditions with the SHRP 2 NDS dataset. The case study shows that pavement surface roughness impacts traffic speed for different full-access-control road scenarios with the listed properties. The research conducted will give other engineers a guidance on how to develop a method to predict speed at different Levels of Service (LOS) given similar road properties on an all access roadway.

Keywords: IRI, roughness-speed relationship, Naturalistic Driving Study data

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CHAPTER 1: INTRODUCTION

Problem Statement

Traffic speed can be determined by speed limit and impacted by road geometry, traffic density (Underwood 1990), and weather (Wang et al. 2014). Speed is an important transportation consideration because it relates to safety, time comfort, convenience, and economics (CTRE Handbook of Simplifies Practice for Traffic Studies; 2002). The influence of different factors on speed is important for modeling vehicle fuel consumption. As a critical road property, pavement surface roughness can influence driving behavior and lead to drivers changing their speed influencing vehicles around them. The roughness-speed relationship (RSR) is a significant factor when modeling fuel consumption. By having a good understanding of how drivers adjust speed on pavements with varying roughness, safety countermeasures related to speed can also be developed or selected. In previous research activities, RSR has been preliminarily studied (Karan et al. 1976; Yu and Lu 2014), but there is lack of comprehensive knowledge about how pavement surface roughness impacts speed under different road and traffic conditions.

The International Roughness Index (IRI) is used to define the quality of pavement surface roughness, and it is used most commonly worldwide (Sayers et al. 1986). IRI is calculated using the response of a quarter-car simulation on a measured longitudinal road profile (Sayers and Karamihas 1998). The IRI objectively measures the cumulative deviation from a smooth surface in inches per mile (Sayers 1995; Plessis 1990). When an IRI becomes higher, the driving vibration is higher resulting in drivers feeling uncomfortable; when the IRI decreases, the quality of the pavement surface becomes better and can provide a smoother ride for the driver. IRI is a data element in the highway performance monitoring system (HPMS) (Office of Highway Policy Information 2014), which is collected and maintained by state Departments of Transportation (DOTs). IRI is widely used to estimate pavement deterioration, section deficiencies, needed improvements for cost allocation studies, pavement condition trends, and other analysis purposes. Table 1 shows the good and acceptable ranges for the IRI that was defined by the Federal Highway Administration (FHWA) (Minnesota DOT 2007). A good IRI range is anywhere under 95 inches-per-mile, while an acceptable IRI range is between 95 inches-per-mile and 170 inches-per-mile. Once the IRI becomes higher than 170 inches-per-mile, it becomes unacceptable and that road will most likely need to be repaired. Currently IRI is a great tool to quantify the quality of pavement surface and it was employed to study the roughness-speed relationship.

Table 1. FHWA IRI Categories

Roughness Category	IRI Value	
	inches/mile	m/km
Good	<95	<1.5
Acceptable	<170	<2.7

Research Objectives

The main goal of this research was to develop a method to study RSR under different road and traffic conditions, while using the SHRP 2 Naturalistic Driving Study (NDS) data. The FHWA conducted a report on determining a relationship between fuel consumption and speed, and the report offered some questions. One of those questions would most likely be what affect does road surface roughness have on vehicle speed on full-access-control highways. The report says that IRI was not a factor that was considered when developing driving cycles, because the influence of pavement on driving cycles had not been well enough determined in a full access control scenario (FHWA 2017). Therefore, this thesis research studied RSR of full-access-control highways by using the developed method and the SHRP 2 NDS data.

The research conducted in this thesis can help engineers out as well in a few different ways. First, this research helps the FHWA answer a question about how the road roughness will impact speeds on a full access control roadway with similar road characteristics. Engineers can also follow the methodology listed in the report to help determine vehicle speeds in other scenarios, such as partial or non-access-control highways. The different scenarios can be based on all kinds of different factors, given the method any factor can be singled out to see how it affects speed or any other factor. The final thing engineers can take away from this research and the major contribution from the research is that engineers can now look at how vehicle speed is impacted by IRI at different levels of service.

Data Set and Methodology

There were a couple of different data sets that were used in completing this research. The first data set that was used was the SHRP2 NDS data set. This data set includes almost all of the information needed to complete this study. The data set itself includes sensor data from a study vehicle, which determined the length to other vehicles around it, speed data which showed a second by second vehicle speed, the data set was extremely comprehensive with over 3,000 participants over three years of study. The next data set used in the study is the SHRP2 road information database (RID), which is the collected to support the SHRP 2 NDS. The RID has a very complex amount of information about the roadway itself that ties NDS and RID data sets together. The NDS data include videos and sensor data so that speed, gps, and video can all be viewed at one moment in time to better understand why a driver could be slowing down or speeding up.

The basis for the methodology began with the NDS and RID data sets. The methodology begins with looking at each trip that was recorded, the trips are then broken down into multiple snippets based on the road properties. If the trip has multiple snippets that have the same IRI then they are grouped together. Next, the radar sensor data was used to detect the number of vehicles around the NDS vehicle and those vehicles distances from the NDS vehicle. With this information, the traffic density can be determined so that a level of service could be estimated for each grouping. After the newly grouped IRI trips were found and their levels of service were determined all of the new snippet trips with the same IRI could be grouped together based on the IRI value as well as level of service.

Literature Review

A few studies have been conducted to analyze the relationship between IRI and speed, however the results of the studies differ. An early research conducted by Karan et al. (1976) analyzed the relationship between speed and IRI using 72 sites near Ontario, Canada. The study was conducted in 1974 and the 72 sites that were examined all had similar characteristics. Those similarities included that they were all two lanes and they were all highways. The information that was taken while on site was vehicle speed, road surface roughness, geometric characteristics and traffic counts. The information collected allowed the authors to create volume over capacity ratios for each site. The authors concluded that the speed drops by about 1.93 mph when IRI increases from 63 to 126 inches-per-mile. This study is very straight forward but some factors are left out including not having a common speed limit and also not looking at how each vehicle is affected by the road roughness given their specific volume over capacity ratio.

Another study by Wang et al. (2014) examined the impact of pavement roughness on free-flow speed. The group that performed this study is a research group at UC Davis and was funded by Caltrans to try to find the impact pavement roughness has on free-flow speed. In this study, a linear regression model of freeway free-flow speed and roughness was developed with data from California freeways. The information that was used to create the model included total number of lanes, days of the week, region, price of gasoline, and pavement roughness in terms of IRI. The data that was used was expansive because it was collected from 2000 to 2011 and because of the number of factors used in the model. The study said that roughly 90% of the data collected was on roads that had what the FHWA describes as an acceptable IRI (less than or equal to 170 inches-per-mile). The research found that it was difficult to develop a relationship between roughness and speed. The research did however find that an IRI change of 63 inches-per- mile caused a drop in vehicle speed of 0.3 to 0.4 miles per hour. While this research was very interesting it may be limited by an overuse of factors and doesn't truly indicate how a more severe IRI could affect speed.

Another study (Yu and Lu 2014) analyzed the roughness effect on vehicle speed by involving 32 different roadway segments with over eight years of data for each segment. The road scenarios are not fixed though, this includes the use of both flexible and rigid pavement and different number of lanes from segment to segment. Through the preliminary data analysis the study determined that pavement type and the speed limit did not have a significant impact on average speed. The obtained regression model reveals that the average vehicle speed decreases 0.0083 miles per hour with every 1 inch-per-mile increase of road roughness. The article by Wang et al. determined that when the IRI increased by 63 inches- per- mile the speed would decrease by 0.3 to 0.4 miles per hour this number is roughly 25% lower than what Yu and Lu discovered.

Another investigation was done that analyzed the relationship between IRI, road capacity, and speed on a two-lane highway in India (Chandra 2004). The IRI samples collected in this study ranged from 126 to 441 inches-per-mile. The study looked at three highways in India, the three highways broke further down into eight different sections. The study concluded that the road roughness negatively correlates with the free-flow speed at the evaluated range of IRI values, and the study also concluded that the capacity lowered when IRI increased. The range of IRI is very large and the amount of extremely high IRI records is very interesting because the majority would be considered in the unacceptable range.

A more recent study examined the influence of roadway factors on 85th percentile of vehicle speed (V85) (Semeida and El- Shabrawy 2016). The IRI was found to have more influence on speed reduction compared to other variables. For 3-lanes highways the increase of the IRI by 63 inches-per-mile led to a drop in V85 by roughly 3.7 miles per hour. The authors also noted that the validity and accuracy of data may constitute the limitations of the results. None of the aforementioned studies considered roughness-speed relationships under different congestion levels and different road scenarios. The goal of this study was to create a relationship between road surface roughness and speed based on different levels of congestion to better understand how a vehicles speed is affected by road surface roughness.

While looking at the effect of road surface roughness on speed is an important, it is also important to look at how road surface roughness effects other factors. One factor that should also be examined is the effect on safety. A study was done on factors that affect road surface properties, it found that most studies had shown there was little effect from ruts on safety unless the road was uneven and the ruts that were abnormal (Ihs and Magnusson 2000).

Another report described its findings on the correlation between safety and surface roughness as being statistically significant effect when ADT (average daily traffic) is taken into account (Mohammed, Umar, Samson, and Ahmad 2015). The same report also said that design considerations such as horizontal and vertical curvatures, numbers of towns/ villages/ intersections on major routes have significant impact on traffic safety. This report shows that the quality of roads has shown to have an effect on safety, but there are many other factors that can be looked at when it comes to safety.

Another very important paper discussed the calculation of the IRI from longitudinal road profile (Sayers 1995). The purpose of the paper was to provide a self-contained description of IRI, including its definition and an algorithm for its calculation. The paper says that in 1982 the “World Bank” conducted a study in Brazil called the International Road Roughness Experiment (IRRE). The results from this experiment concluded that all thee roughness measuring instruments around the World were capable of producing measurements on the same scale so an objective was developed from the experiment: to develop the IRI scale. The group found that using the Quarter car simulation to develop the IRI scale was optimal. The quarter car simulation could measure true profiles over a range of wavelengths that affect vehicle vibrations. IRI is calculated from a single longitudinal profile, the required resolution for the sample depends on the roughness level itself. A finer resolution is needed for smoother roads; a resolution equivalent to 0.02 inches is suitable for all calculations. It is assumed that the profile has a constant slope between elevation points.

In another paper from the World Bank, the guidelines for conducting and calibrating road roughness measurements were laid out (Sayers, Gillespie, and Paterson 1986). The World Bank is the group that came up with and defined the International Roughness Index and they describe it as follows: "The international Roughness Index (IRI) is defined, and the programs for its calculation are provided. The IRI is based on simulation of the roughness response of a car travelling at 80 km/h - it is the Reference Average Rectified Slope, which expresses a ratio of the accumulated suspension motion of a vehicle, divided by the distance travelled during the test." The paper also defines a way to translate speeds that are not at the test speed of 80 km/h to an IRI value.

It is also extremely important to look at environmental effects that are caused from vehicles being on the road for longer amounts of time, the FHWA (2016) looked at enhanced prediction of vehicle fuel economy and other vehicle operating costs. The report that the FHWA conducted focused on developing driving cycles - speed-time profiles under different highway and traffic conditions. The report stated that fluctuation in vehicle speed can lead to an increase in vehicle operation costs, and in addition to operation costs the longer a vehicle is on the road the more emissions they output to the environment. The report also said that IRI was not considered a factor when generating the driving cycles; this was due to the difficulty in isolating the influence pavement roughness has on driving cycles. The FHWA describes pavement roughness as an unknown factor on vehicle speed and therefore they are unable to link it with any environmental impacts.

Organization of the Thesis

This thesis encompasses a total of four chapters, which includes the introductory chapter. The second chapter discusses the data processing part of the research. This includes the use of RID data processing as well as NDS data processing. The chapter also discusses how the vehicle sensor data was used to create a level of Service density. The following chapter covers the methodology for identifying the road surface roughness. Chapter three takes a look at level of service A, B, C, D, and E individually. This chapter also looks at a combination of all the level of services together so a better comparison can be made in identifying their trends. The final chapter is chapter four that makes conclusions on the research that was done. The final chapter includes a comprehensive discussion about the conclusions as well as it goes over future works to make the research more complete.

CHAPTER 2: DATA PROCESSING

With new technologies and data collection methods, new transportation data sets have been collected within the past few years. These new datasets bring opportunities to identify RSR under different conditions, which was impossible before due to dataset limitations. The Strategic Highway Research Program 2 (SHRP 2) naturalistic driving study (NDS) data (Blatt 2014) and the related road information database (RID) (Smadi, Hawkins, Hans, and Bektas 2014) represent the latest dataset used to further this research. The NDS data include time-series records from the different sensors installed on the volunteer vehicles and offer multi-direction video clips, an example of this is shown in Figure 1. The timestamp is shown in a red box in the upper left part of the figure, the timestamp. The RID contains comprehensive roadway and environmental data related to the NDS road network. The NDS data was collected by 3,100 volunteers at six sites in the United States: Tampa, Florida; central Indiana; Durham, North Carolina; Erie County, New York; central Pennsylvania; and Seattle, Washington. The data collection lasted from 2010 through 2013. In this paper, part of the SHPR 2 NDS data were used to analyze RSR.

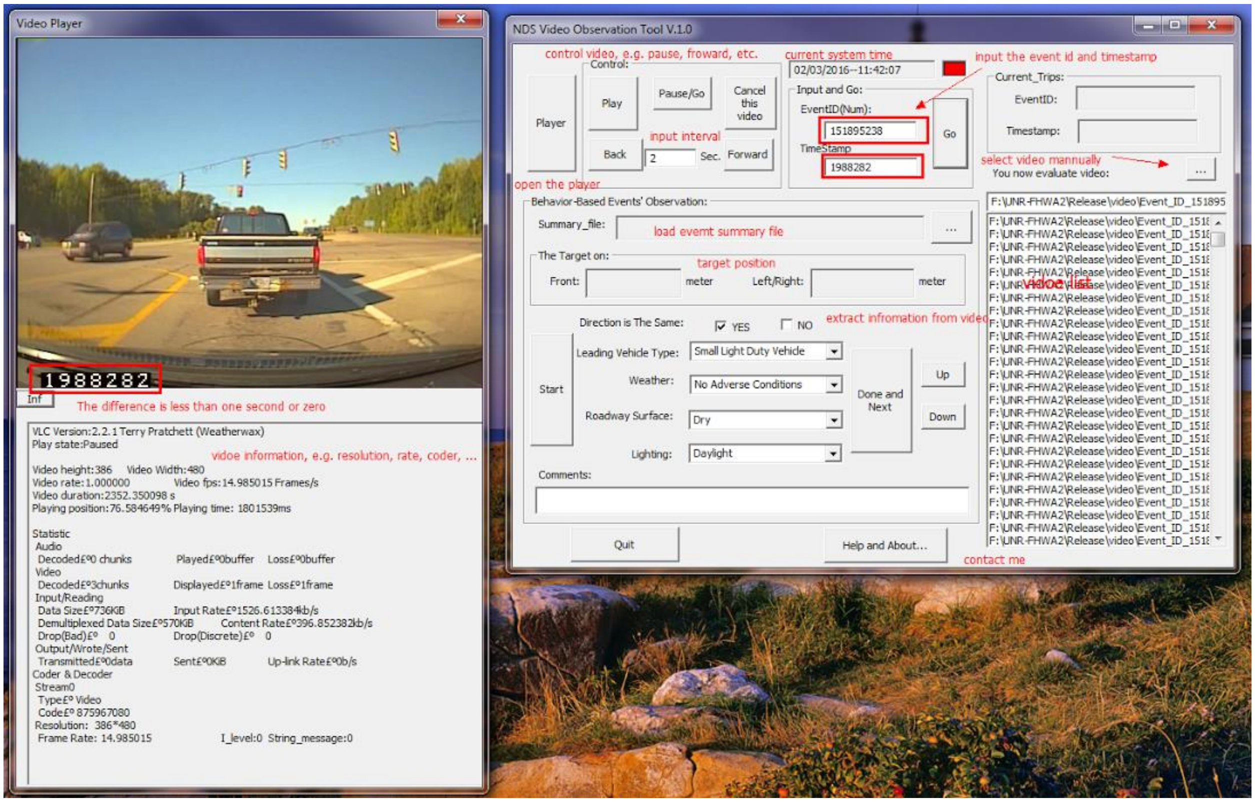

Figure 1. User interface of the NDS Front Video Review Tool

A total of 4,400 trips collected at the six NDS sites were obtained for RSR analysis. Each trip is at least 20-minute long and one trip can cover road segments with different IRI values. To study RSR of different road conditions, the SHRP 2 NDS data was integrated with the RID data and grouped by road properties. The vehicle trajectories of NDS data in each road group are then further classified based on densities that can be further converted to traffic Level of Service (LOS). Table 2 shows how extensive the NDS and RID database are.

Table 2. Summary of SHRP 2 Safety Data (Enhanced Prediction of Vehicle Fuel Economy and Other Vehicle Operating Costs)

Data	Description
Naturalistic Driving Study (NDS)	Six data collection sites: Tampa, Florida; Central Indiana; Durham, North Carolina; Erie County, New York; Central Pennsylvania; and Seattle, Washington.
	3,147 drivers, all age/gender groups.

	3,958 data years; five (5) million trip files; 49.7 million vehicle miles.
	Three (3) years of data collection.
	Vehicle types: light duty vehicles.
Road Information Database (RID)	Four (4) different data sources.
	ESRI: baseline data for entire country.
	State roadway inventory data from six (6) State studies.
	Mobile van data: very detailed, about 12,500 centerline miles; 43,195 intersections, 518,570 MUTCD signs; includes forward video.
	Supplemental data from six (6) State studies.

It was also extremely important that all the NDS data-collection sites had similar attributes in the local study area. The site attribute selection also considered the data availability to researchers and engineers. The identified eight site attributes are listed as the following:

- Geographic characteristics
- Population
- Education attainment
- Household income
- Weather
- Traffic safety laws
- Median driver age
- Historical crash data

By the end of the study, a total of 4,368 participant-years data were collected from 3,542 drivers. The final SHRP 2 NDS database is about 2 petabytes (2,000 terabytes), including 5.5 million trip files and 32.5 million vehicle miles. There were 1,600 crashes and 2,900 near-crashes recorded. The volunteers of the project had their vehicles with NDS data acquisition systems (DASs) which included cameras, radar, and other sensors to capture data during their usual driving tasks. A summary of the NDS DAS instruments can be seen in Table 3. Following Table 3 is Table 4 which gives the breakdown in DAS units at each of the six sites and gives general information about every site listed.

Table 3. Summary of Instrumentation in DAS (Usage Guidelines of SHRP2 Naturalistic Driving Study Data for Nevada)

Instrumentation	Notes
Four video cameras	2 outward (1 color, 2 wide angle view) and 2 inward-viewing black & white video
Still image camera	Periodic image to detect number of people in vehicle
Accelerometers (3 Axis)	Lateral, longitudinal, and vertical vehicle accelerations
Rate Sensors (3 axis)	Lateral (turning), longitudinal and lateral (roll) rate
GPS (with antenna)	Latitude, longitude, elevation, time, velocity
Forward radar (on front bumper) & radar interface box (RIB)	X, Y positions & X, Y velocities of objects in front of vehicle
Cell phone (with antenna)	Automatic crash notification; vehicle location notification, health checks, remote upgrades
Illuminance sensor	Level of luminance outside vehicle (day/night indicator)
Infrared illuminator	To enable viewing of driver's face at night by camera
Passive alcohol sensor	Intended to detect nominal amounts of alcohol in cabin air. NOT driver specific. May also detect alcohol from topical sources (hand sanitizer, etc.).
Incident push button	Audio recorded only if button pushed
Turn signals (other lights?)	State of turn signal (on/off) recorded
Vehicle network data (cabling to connect DAS with OBD)	Accelerator, brake pedal activation, automatic braking system (ABS), gear position, steering wheel angle, speed, horn, seat belt information, airbag deployment and other data

Table 4. Areas and Unique Features of the Six NDS Sites (Usage Guidelines of SHRP2 Naturalistic Driving Study Data for Nevada)

Study Center Area Name (State)	Recruiting Area Defined by	Counties Within Study Center Recruiting Area (Major and Minor Contributors)	Unique Features Within Area	Nominal Number of DAS Units Assigned

Bloomington (Indiana)	39 zip codes inprimary area; 25 zip codes in secondary area (64 total)	Major/Primary (11): Brown, Dubois, Greene, Johnson, Lawrence, Martin, Monroe, Morgan, Orange, Owen, Putnam Minor/Secondary (6): Marion, Bartholomew, Clay, Davies, Jackson, Shelby (8% of participants from secondary)	• Large parts of the Hoosier NationalForest and the Deam Wilderness area • Naval Surface Warfare Center Crane located in Martin County • Camp Atterbury located in BartholomewCounty • Primary area mostly rural, agricultural; secondary area more urban	150
Buffalo (New York)	1 county	Major/Primary: Erie Minor/Secondary: Niagara (4% of participants) and Cattaraugus (0.2% of participants)	• One international border crossing withinprimary study center area C Peace Bridge, Buffalo, NY • Additional features just outside primaryarea C Three additional U.S./Canada bridge crossings (Niagara County) C Niagara Falls Air Force Base (Niagara County)	450
Durham (North Carolina)	39 zip codes	Major/Primary: Chatham, Wake, Orange, and Durham Minor/Secondary: Granville, Johnston, andHartnett (less than 5% of county areas)	• Durham is in North Carolina's central piedmont, a geographic region lying nearly equal distance between themountains and coastal plains.	300
Seattle (Washington)	3 counties	Major/Primary: Snohomish, King, and Pierce	• Two military bases within primary studycenter area: C Joint Base Lewis-McChord (south ofTacoma in Pierce County) C Puget Sound Naval Complex in Everett, Snohomish County • Additional features just outside primary area: C Whidbey Island Naval Air Station, northwest of Snohomish County C Several U.S./Canada border crossings (e.g., Vancouver, B.C.) within a few hours' drive north of primary driving area	420
State College (Pennsylvania)	10 counties	Major/Primary: Blair, Cambria, Centre,Clearfield, Clinton, Huntingdon, Juniata, Mifflin, Snyder, Union	• Although mostly rural, area featuresinclude rugged mountainous environ-ments as well as sweeping, rolling valleys.	150
Tampa (Florida)	2 counties	Major/Primary: Hillsborough and Pasco Minor/Secondary: Pinellas	• MacDill is an active U.S. Air Force base located in Tampa, Florida.	450

RID Data Processing

The SHRP 2 RID contains properties of 4,500-mile roadway at the six SHRP 2 NDS data collection sites (Smadiet al. 2014). The RID dataset is composed of multiple GIS layers. To measure the RSR, it is important to exclude the influence of other road factors on speed (Wang et al. 2014). Road factors that were excluded from analysis included: lighting, weather conditions, partial access control roadways, varying number of lanes, and many more. Therefore, RSR was studied in each specific road scenario with unique properties. The query conditions were created for selecting road segments of various road scenarios. The HPMS layer in RID and other layers with different road features were first integrated. Grouping of road segments considered the following road properties: access control type, facility type, rural/urban area, speed limit, and lane number.

The RID database is so comprehensive and it allowed this research to include many different factors in the analysis. The SHRP 2 NDS database that includes this RID database can also help a lot of engineers and researchers in the future, this is due to the use of so many different data elements. The major data elements that were used in the database are listed in the following.

- Horizontal curvature:
    - Radius
    - Length
    - Point of curvature (PC)
    - Point of tangency (PT)
    - Direction of curve (left or right based on driving direction)
- Grade

- Cross-slope/ Super elevation
- Lanes: number, width, and type (turn, passing, acceleration, car pool, etc.)
- Shoulder type/curb (and paved width, if it exists)
- All Manual on Uniform Traffic Control Devices (MUTCD) signs
- Guardrails/Barriers
- Intersection: location, number of approaches, and control (uncontrolled, all-way stop, two-way stop, yield, signalized, roundabout). Ramp termini were considered intersections.
- Median presence: type (depressed, raised, flush, barrier)
- Rumble strip presence: location (centerline, edgeline, shoulder)
- Lighting presence

NDS Data Processing

The NDS time-series data of each trip includes speed, acceleration, location, time, front radar data and other trip information of the volunteer vehicles. NDS data records were filtered to exclude records with invalid position information. The validated records were then spatially joined to the grouped roadway segments to obtain trip snippets for different road scenarios. The spatial-join procedure applied 300 feet round buffer to find road segments near data records and then identified the closest road segment as the matched one of the NDS data record. This procedure is named “map-matching” (Dalumpines and Scott 2011). After the spatial-join, highway properties of matched segments were appended to the related NDS data record and an extended dataset was created. The NDS data records were classified into the different highway scenarios. For the NDS trip data in each road scenario, trip snippets were further segmented by their IRI values. A continuous trip snippet is segmented if the pavement IRI value changes. To illustrate the data processing and RSR analysis methodology, a road scenario was selected as the case-study example. In this case study, all the data that was selected included the same properties: light duty vehicle, good weather (sunny), a speed limit of 60 mph, three lanes in each direction, urban area, two-way roadway, and full-access-control freeway.

Radar Data Processing for Density

Each NDS vehicle was equipped a DAS unit that included an eight-channel radar sensor. The sensor is able to detect a maximum of eight objects (vehicles) in front and around the NDS vehicle and reports the longitudinal distance and the vertical distance of each detected object. The eight-channel radar data is included in the NDS time series dataset, and this information contained the number of vehicles detected and their distances to the NDS volunteer vehicle. With the radar data, an average distance between the NDS vehicle and front vehicles could be calculated using Equation 1. The average distance is then converted to density using Equation 2. The traffic density is calculated for each NDS data record that was archived at the frequency of 1 HZ. The average density is converted to LOS by Table 5.

Table 5. LOS based on Density (Transportation Research Board 2010)

Level of Service	Density (pc/mi/lane)
A	≤11
B	>11-18
C	>18-26
D	>26-35
E	>35-45
F	>45 or any component v_d/c ratio >1.00

Note: LOS F is characterized by highly unstable and variable traffic flow. Prediction of accurate flow rate, density, and speed at LOS F is difficult. So LOS F was not covered for RSR analysis in this research.

$$\underline{d} = \frac{\Sigma\, d}{\Sigma\, V} \qquad (1)$$

Where $\underline{d}$= average distance (ft)

d= distance from NDS vehicle to tracked vehicle (ft)

V= Number of tracked vehicles

$$D = \frac{5280 ft}{\underline{d}} \times \frac{\Sigma\, V}{N} \qquad (2)$$

Where D= density

N= number of lanes on one side of the roadway (3 in all cases, for this thesis)

$\underline{d}$= The average distance of a tracked vehicle from the NDS vehicle

V= Number of tracked vehicles

An example of density estimation was provided. In a freeway having three lanes in one direction shown in Figure 2, three front vehicles were tracked by the NDS vehicle. Based on the tracked distances, the estimated density was calculated as 41.7 vehicle per lane per mile based on Equation 1 and Equation 2 in the calculations below.

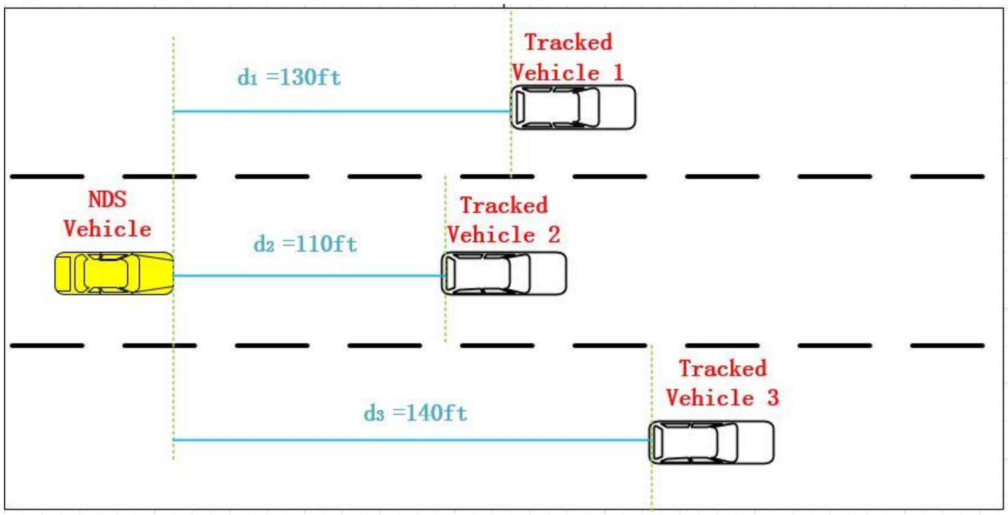

Figure 2. Map of Vehicle Density Calculation

$$\underline{d} = \frac{130+110+140}{3} = 126.7ft$$

$$D = \frac{5280}{126.7} \times \frac{3}{3} = 41.7\text{pc/mi/ln}$$

For the sample road scenario, the total available trip segments for different LOSs along with their respective IRI and speed ranges and average values are shown in Table 6. Table 6 shows the minimum speed under different LOSs is pretty low, such as 37.28 mph under LOS A. The raw files of the NDS data were checked to identify any possible reason. It was determined that these low speed records occurred at off-ramps or local streets, not freeways, which is caused by a data error in HPMS layer. These records were then removed from the database.

Table 6. Available trip segments for different LOS

LOS	Total trip segments	IRImin (inch/mile)	IRImax (inch/mile)	IRIaverage (inch/mile)	Speedmin (mph)	Speedmax (mph)	Speedaverage (mph)
A	69	45	133	83.47	37.28	75.19	61.97
B	58	45	128	80.07	45.57	68.48	58.20

C	90	45	133	82.68	44.25	65.84	54.93
D	88	45	133	86.26	24.70	67.74	52.16
E	108	45	133	85.59	20.34	71.96	49.85

Now that a structure for the method was created, it can be explained in terms of a flow chart in Figure 3. The very first step is to select the road properties for the scenario and look for road segments with those properties. Next we have to break the trip down into different grouped segments. Once the trip is broken down into the segments of interest, those segments properties can be examined more closely. If the segment in question has more than one IRI value on it, each portion of that trip will be its own "snippet". If there is only one IRI on that segment there is only one snippet. Next the snippets are examined for their speed and radar information. From that step equations 1 and 2 are used to calculate a density, that density then groups the snippets into a level of service. Finally all the snippets in each LOS can be examined by a statistical analysis software. This procedure allows one to isolate IRI values and LOS and examine how speed is impacted at each level of service.

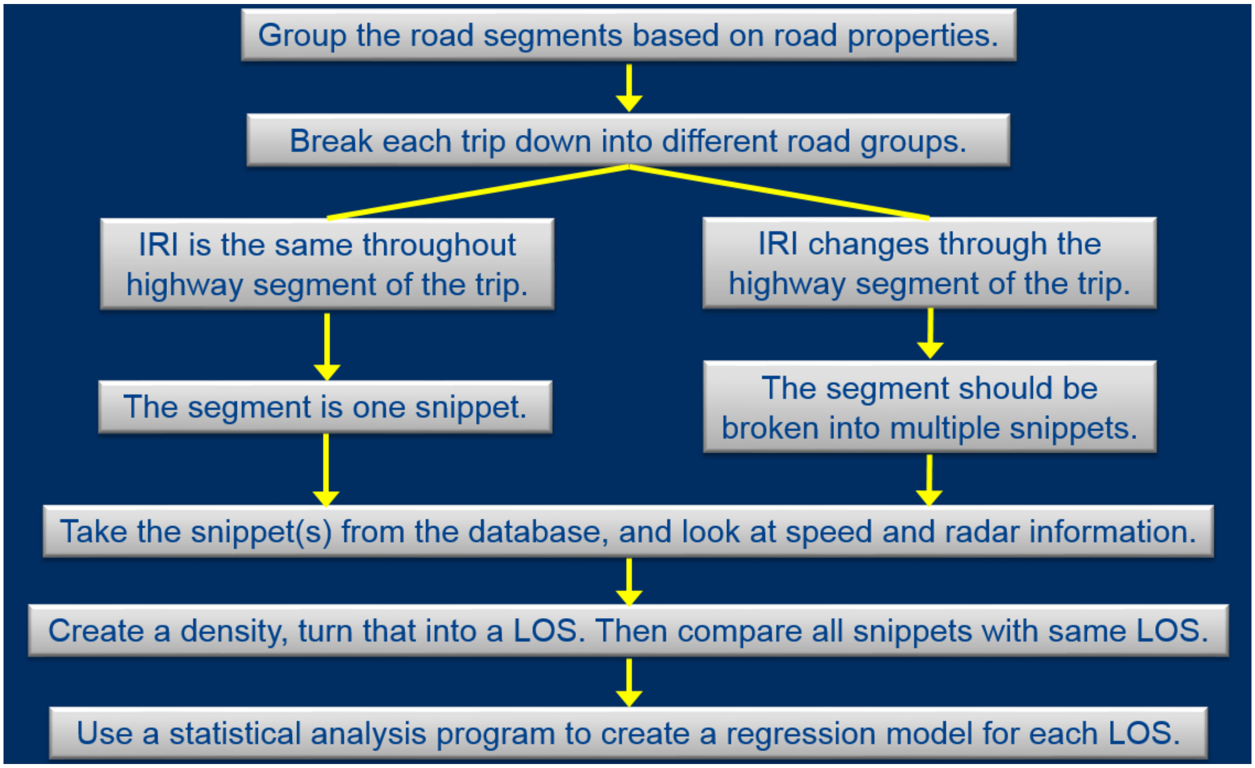

Figure 3. Proposed Data Processing/ Analysis Method

CHAPTER 3: METHODOLOGY OF IDENTIFYING RSR

A regression model was built based on the data prepared in the Data Processing section. The software Origin was employed to fit curves for its powerful function of linear, polynomial, and nonlinear curve fitting along with validation and goodness-of-fit tests (Xu- Hong 2006). Origin provides more than 170 built-in fitting functions for curve fit. The top three functions: Logistic, Allometric, and Poisson models can successfully fit the curve between IRI and speed in Origin. The output of Origin also generated the Residual Sum of Squares (RSS). The RSS of the example road scenario are shown in Table 7. The logistic model has the lowest residual sum of squares, which indicates that logical model can fit the data more closely than the other models. To further identify the best curve, the Akaike's Information Criterion (AIC) (Akaike 2011) and Bayesian Information Criterion (BIC) (Weakliem 1999) were calculated to identify the best model. The best model is considered to have a smaller AIC and smaller BIC. The AIC and BIC of each models generated for the sample scenario are also shown in Table 7. Comparing the RSS, AIC and BIC, the logistic model was identified as the best curve for all LOSs.

Table 7. Regression Summary

LOS	Model	Equation	Adj R-Square	Residual Sum of Squares	AIC	BIC	Best Curve
A	Logistic	y=A2+(A1-A2)/(1+(x/x0)^p)	0. 23	3201.2	468.7	475.3	√
	Allometric	y =a*x^b	0.15	3628.9	468.0	474.7	
	Poisson	y =y0+e^(-r)*r^x/(x!)	-0.02	4359.6	None	None	
B	Logistic	y=A2+(A1-A2)/(1+(x/x0)^p)	0. 41	837.4	326.8	333.0	√
	Allometric	y =a*x^b	0. 41	864.2	353.1	359.3	
	Poisson	y =y0+e^(-r)*r^x/(x!)	−0. 02	1499.3	None	None	
C	Logistic	y=A2+(A1-A2)/(1+(x/x0)^p)	0. 22	2044.3	550.6	558.1	√
	Allometric	y =a*x^b	0. 16	2252.5	564.9	572.3	
	Poisson	y =y0+e^(-r)*r^x/(x!)	−0. 01	2724.3	None	None	
D	Logistic	y =A2+(A1-A2)/(1+(x/x0)^p)	0. 07	5591.8	621.2	628.6	√
	Allometric	y =a*x^b	0. 09	5606.0	623.4	630.8	
	Poisson	y =y0+e^(-r)*r^x/(x!)	−0. 01	6222.3	None	None	
E	Logistic	y=A2+(A1-A2)/(1+(x/x0)^p)	0. 23	9373.2	798.0	806.1	√
	Allometric	y =a*x^b	0. 22	9754.7	817.2	825.3	
	Poisson	y =y0+e^(-r)*r^x/(x!)	−7. 41	104771.0	None	None	

The relationship between IRI and speed of the sample scenario was generated for LOS A through E by using the logistic regression model. The following part shows the RSR under different LOSs of the sample scenario.

LOS A

LOS A represents the traffic condition of low density and free-flow speed. The average speed for each trip snippet of LOS A was ploted in Figure 4. There were a total of 68 different trip snippets in LOS A of the sample scenario. The range of the IRI values of these trip snippets was 45 to 133 inches-per-mile.

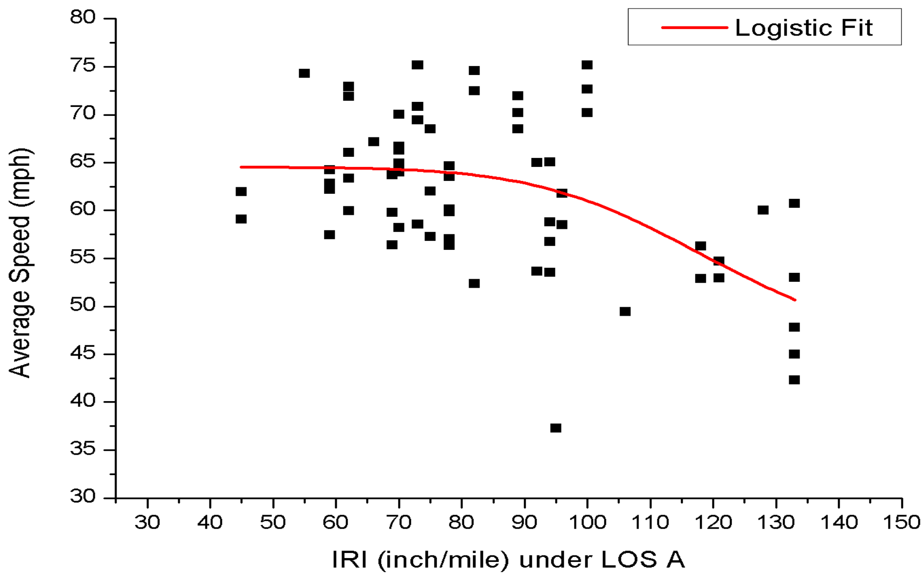

Figure 4. LOS A showing the IRI vs. Average Speed

A logistic curve fit was applied to describe the trend of the speed as the IRI changes. The IRI-speed relationship curve in Figure 4 showed that when IRI is under 95 inches- per- mile, the speed is fairly high and does not reduce much when IRI value increases. When IRI is higher than 95 inches- per- mile, vehicle speed reduces more quickly with the IRI value increasing. The fitted curve is expressed by Equation 3. This function can be used to estimate traffic speed at a given IRI for LOS A of the sample scenario. Similar curves and functions can be developed for other road scenarios with the introduced methodology.

$$y = 44.05 + \frac{20.48}{1+\left(\frac{x}{121.47}\right)^{8.07}} \tag{3}$$

Where x = IRI (inches-per-mile)

y=speed (mph)

LOS B

LOS B represents higher density, but traffic is still close to a free flow condition. For LOS B, the available NDS data of the sample scenario covered the IRI range of 45 to 128 inches- per-mile. There were 58 trip snippets in LOS B of the sample scenario. The IRI-speed relationship is plotted in Figure 5.

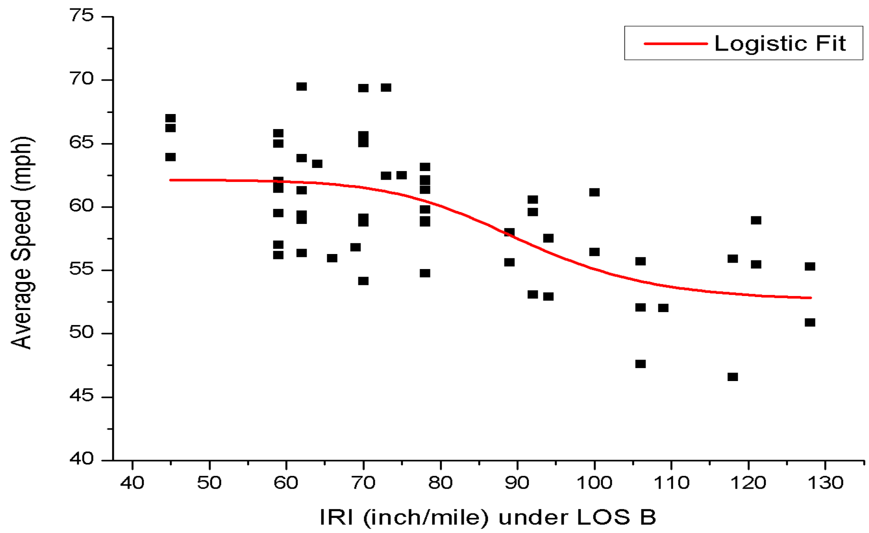

Figure 5. Average Speed vs. IRI for LOS B

The density of LOS B is higher than that of LOS A. The average speed is more than 60mph when IRI is less than 70 inches-per-mile. The curve starts to decline after the IRI of 70 inches- per- mile. The curve levels off when the IRI is in the range of 110 to 128 inches-per- mile. The logistic formula for this RSR curve is shown in Equation 4.

$$y = 52.56 + \frac{9.57}{1+(\frac{x}{90.58})^{10.36}} \qquad (4)$$

Where x = IRI (inches-per-mile)

y=speed (mph)

LOS C

A road at of LOS C provide a stable traffic flow that is near free flow. The trip data for LOS C of the sample scenario covers the IRI range of 45 to 133 inches-per-mile, which includes 90 trip snippets. Figure 6 shows how IRI affects the average speed of LOS C.

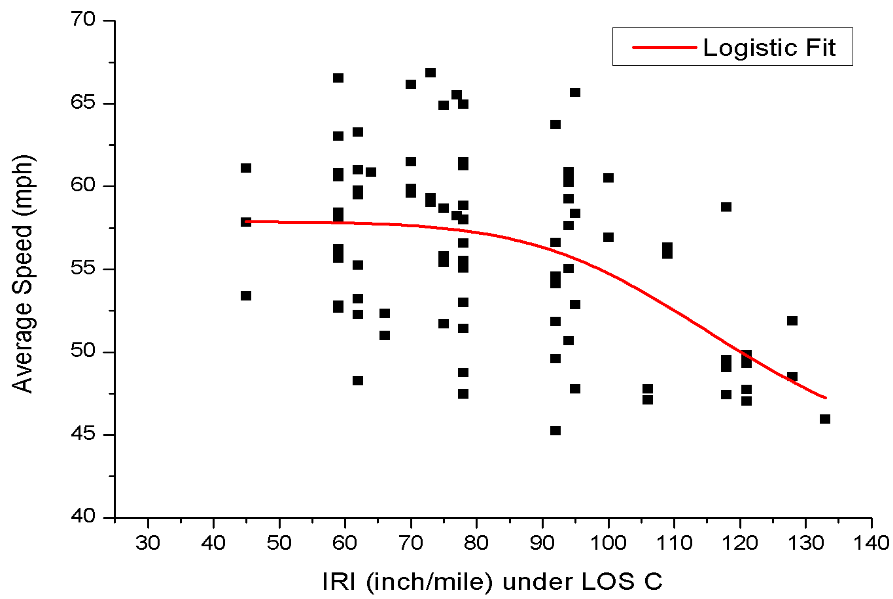

Figure 6. IRI's effect on average speed for LOS C

The IRI turning point of the curve in Figure 6 is around 80 inches-per-mile. When the IRI is larger than 80 inches-per-mile, the average speed drops quickly as the IRI increases. The equation of the logistic fitting curve is shown in Equation 5.

$$y = 42.94 + \frac{14.93}{1+(\frac{x}{118.49})^{7.85}} \quad (5)$$

Where x = IRI (inches-per-mile)

y=speed (mph)

LOS D

Traffic flow is approaching unstable with LOS D. The average speed for each trip snippet of LOS D is plotted in Figure 7. A total of 88 different trip snippets were identified for LOS D of the sample scenario. The range of the IRI value is from 45 to 133 inches-per-mile.

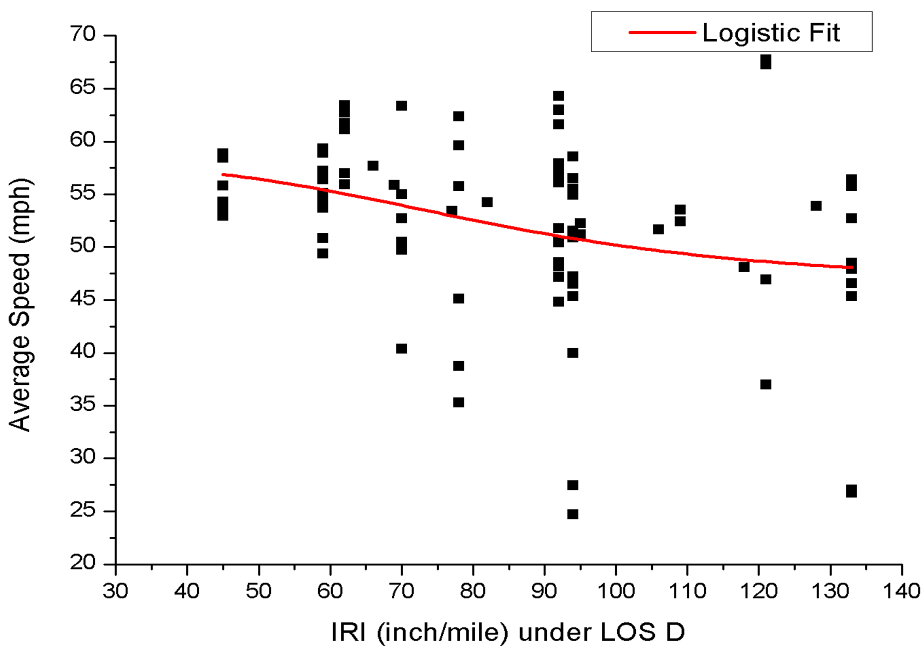

Figure 7. Average Speed vs. IRI for LOS D

The IRI turning point of LOS D is not obvious in Figure 7. The average speed of the trips decreases gradually as the IRI increases. The formula for the curve is shown in Equation 6.

$$y = 46.47 + \frac{11.39}{1+(\frac{x}{82.86})^{3.84}} \qquad (6)$$

Where x = IRI (inches-per-mile)

y=speed (mph)

LOS E

Traffic flow becomes irregular and speed fluctuation is huge under LOS E. LOS E of the sample scenario contained data for IRI range of 45 to 133 inches-per-mile. A total of 108 trip snippets were obtained for LOS E of the sample scenario, this is the largest amount of trips for any LOS. Figure 8 shows how the IRI affects the average speed in LOS E.

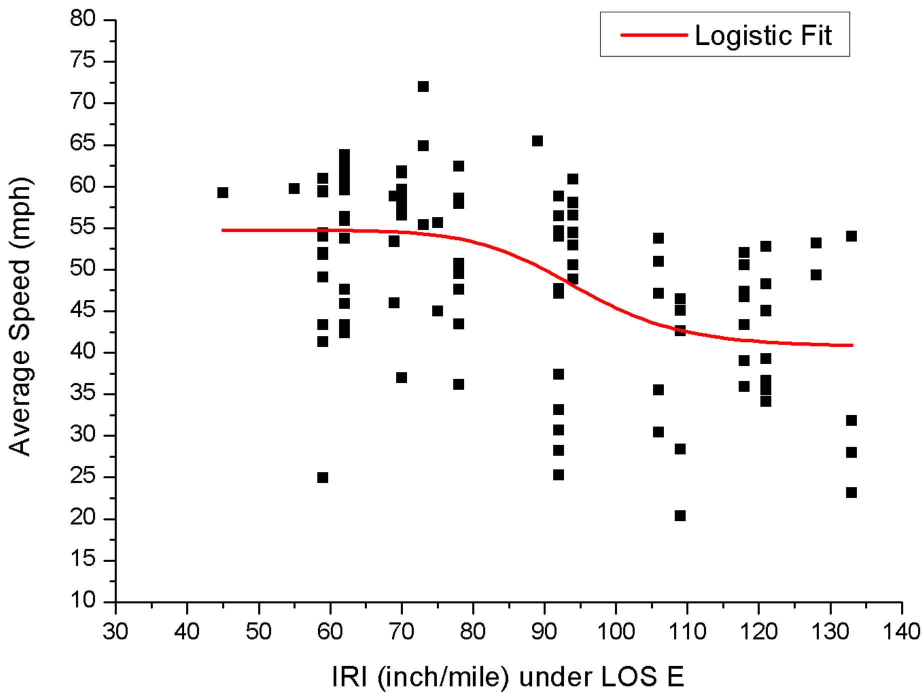

Figure 8. Average Speed based on IRI at LOS E

The data in Figure 8 is very spread out, which can also be seen from the high RSS (9373.2) of logistic fit from Table 5. Under congested conditions, the interactions between vehicles can have a substantial effect on a vehicle's speed. The driver's desire to drive faster on a smooth pavement will be interrupted by the speed fluctuation (Wang et al. 2014). The curve in Figure 7 still shows the similar trend as other LOSs: average speed decreases as IRI increases. The formula for the curve is shown in Equation 7.

$$y = 40.72 + \frac{14.06}{1+(\frac{x}{94.71})^{12.85}} \tag{7}$$

Where x = IRI (inches-per-mile)

y=speed (mph)

RSR under Different LOS

The IRI-speed relationship curves for different LOSs of the sample scenario is compared in Figure 9.

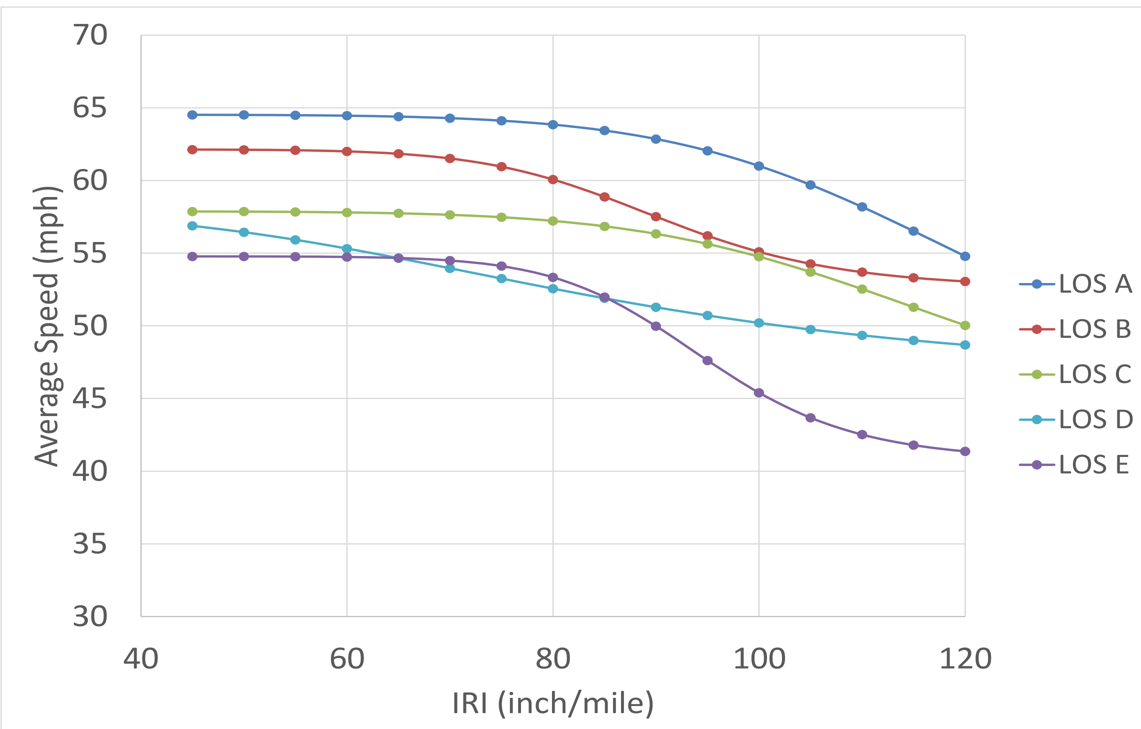

Figure 9. Combined LOS, for IRI vs Average Speed

The trends of these curves are similar: speed is stable when the IRI is low and speed decreases quickly when IRI reaches a high value. With different IRI value, the speed change could be divided into two stages. The first stage is at an IRI value of 80 inches-per-mile. When IRI is smaller than 80 inches-per-mile the speed does not change much as the IRI increases. When IRI is greater than 80 inches-per-mile, the average speed drops quickly as the IRI increases.

CHAPTR 4: CONCLUSIONS AND FUTURE WORKS

Conclusions

This paper introduces a new methodology to identify roughness-speed relationships for different LOSs and road scenarios with the SRHP 2 NDS and RID data. Although only relation curves and functions of one sample scenario are presented in this paper, the data processing procedure and the regression analysis can be applied to develop the roughness-speed relationships of other road scenarios. Major findings of this study are summarized as follows:

- The roughness-speed relationships of different road and traffic conditions can be identified by using the proposed new method and the SHRP 2 NDS data.
- The roughness-speed relationships can be expressed as logistical functions.
- Each LOS provides a different IRI-versus-speed profile.
- The trend of roughness-speed relationships could be divided into two stages: in the first stage, IRI only has a minimal effect on the average speed when IRI is low; and in the second stage when IRI reaches a high value, speed decreases quickly. The threshold IRI value of the two stages of the sample scenario is an IRI of 80 inches-per-mile.

Discussions and Future Works

This research used a new dataset, the SHPR 2 NDS and RID data, to analyze the roughness-speed relationship. The quantity and quality of the SHRP 2 data used in this research outperforms data used in previous research. This paper demonstrated a case study for the RSR analysis of a specific road scenario. The RSR analysis under different scenarios could be performed by using the same method. The results could help to understand the detailed influence of roughness on speed. This knowledge is significant for traffic fuel consumption and traffic safety. However, the IRI range of the sample scenario data is only from 45 inches-per-mile to 133 inches- per- mile, which does not cover IRI values in the unacceptable range of 170 inches- per-mile or greater. The analysis of the influence of high IRI greater than or equal to 170 inches- per-mile on speed can be studied in the future using more NDS data. This study used trips under normal weather condition (without rain, snow or other extreme weather) to eliminate the influence of weather. The analysis of RSR under different weather conditions could be conducted in the future studies.

Abbreviations

The following symbols are used in this paper:

RSR= Road Surface Roughness

IRI= International Roughness Index

NDS= Naturalistic Driving Study

SHRP2= Strategic Highway Research Program 2

RID= Road Information Database

HPMS= Highway Performance Monitoring System

FHWA= Federal Highway Administration

D= density

d= distance (ft)

$\underline{d}$= average distance (ft)

N= number of lanes

V= vehicle

x = IRI (inches-per-mile)

y=speed (mph)

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